

Stream Sediment Monitoring on the Klamath National Forest 2009 to 2011

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ABSTRACT: State water quality regulations require the Forest Service to conduct in-channel sediment monitoring to determine if beneficial uses are being adversely affected by management activities. Streambed sediment deposition was measured in low gradient stream channels located near the mouth of 69 watersheds on the Klamath National Forest, California. Reference conditions were developed from 20 reference streams for V^* , percent fine sediment on the riffle-surface, and percent fine sediment in the streambed subsurface. When compared to reference streams, 22 managed streams had sediment greater than the reference condition for at least one indicator. Of these, 16 streams have cumulative in-stream impacts due to human-caused sediment sources and are not attaining desired conditions for riparian reserves. We found significant but weak correlations between in-stream sediment and land disturbance modeled by the equivalent roaded area, GEO mass wasting, and USLE surface erosion models. Watersheds underlain by geologic parent materials that produce sand-sized particles, or that contain stream channels with low stream-power could tolerate less disturbance without exceeding the reference condition for sediment. New thresholds for the ERA, GEO, and USLE models can be identified where linear regressions predict attainment of reference conditions, but the accuracy of the predicted sediment is very low. V^* responded to increased sediment supply in non-sandy watersheds, indicating that V^* can be used as a method to measure the effects of disturbance in both sandy and non-sandy watersheds.

INTRODUCTION

This report is an assessment of in-stream sediment data collected on the Klamath National Forest between 2009 and 2011. The monitoring program is designed to meet the Forest Service monitoring requirements in the Klamath, Scott, Shasta, and Salmon River TMDLs, and two memoranda of understanding between the Forest Service and the North Coast Regional Water Quality Control Board (NCWQCB 2009a, b). The program also meets the in-channel monitoring requirement for projects covered under Category B of the Regional Water Board's Categorical Waiver for management activities on federal land (NCRWQB 2010).

The purpose of in-channel sediment monitoring is to assess whether current and past management activities have had a cumulative adverse impact on beneficial uses. Past activities may include recent management actions taken under the current Land and Resource Management Plan (Forest Plan), and previous land uses that left legacy sediment sources. Water quality on Forest Service lands is managed through application of best management practices (BMPs), adaptive management, and restoration of legacy sites. Additional water quality protection is provided through agency directives, manuals, handbooks, and Forest Plan standards and guidelines. The sediment monitoring program evaluates the

combined effectiveness of these multiple policies at the watershed scale. On-site monitoring of individual BMPs is evaluated using a different protocol and is reported in a separate report (USFS 2011b).

The objectives of the monitoring program are to answer the following questions:

1. What is the reference condition for stream sediment on the Klamath National Forest?
2. Are Forest Service water quality policies effective at maintaining or restoring desired conditions that support beneficial uses?
3. Identify thresholds for the Forest Service cumulative watershed effects models that predict attainment of desired conditions for stream sediment.

METHODS

In-stream sediment is measured using the parameters and methods listed in Table 1. The sample design and a Quality Assurance Project Plan were approved by the North Coast Regional Water Quality Control Board in 2010. A detailed description of the sediment sampling protocols and field forms are available in the Klamath National Forest stream monitoring field guide (Elder 2009).

Compliance Criteria

Both the North Coast Regional Water Quality Control Board and the Forest Service have established criteria for in-stream sediment. The North Coast Water Board has developed desired condition values for sediment indices that are expected to support beneficial uses and meet the Basin Plan objectives for sediment (Table 1, NCRWQCB 2006 and 2007). The Forest Service desired condition for water quality in riparian reserves simply refers to the State water quality requirements (USFS 1994). The Forest Plan also contains a numeric standard of 15% streambed-surface sediment. However, the state's desired condition values were derived from watersheds underlain by the Franciscan Formation and may not reflect the size and volume of sediment produced from the parent material on the Klamath National Forest. Many of the values were developed from literature documenting the habitat needs of salmonids and do not necessarily represent the potential condition of streams on the Klamath National Forest.

To help identify more appropriate values for the desired condition, the Klamath National Forest and the North Coast Regional Water board have agreed to monitor sediment in reference streams to develop local values for the indices in Table 1. Compliance is evaluated by comparing sediment in each individual managed stream to the 75th percentile of the reference values (Stoddard et al, 2005). The hypothesis tested is:

$$H_0: S_m \leq S_r + e$$

Where: S_m = Value of a sediment indicator in a managed stream
 S_r = 75th percentile of sediment values in reference streams
 e = Survey error

TABLE 1. Parameters used to measure attainment of water quality standards for sediment.

Parameter	Desired Condition	Source	Survey Method
Fraction of Pool Volume filled with Sediment (V*)	≤ 0.21 (21%)	Scott River TMDL (2007) NCRWB (2006)	Hilton and Lisle (1993)
Subsurface Sediment			
Percent < 0.85mm	$\leq 14\%$	Scott River TMDL (2007)	Schuet-Hames (1999)
Percent < 6.4mm	$\leq 30\%$	NCRWB (2006)	Valentine (1995)
Surface Sediment			
Percent < 2.0mm	$\leq 15\%$	USFS (1994)	USFS (2003), Cover (2008)

Selection of Watersheds and Sample Sites

A network of monitoring watersheds was developed that covers all of the major tributary streams on the Klamath National Forest (Figure 1). One sample site was selected in each watershed at a “response reach”. Response reaches usually have the lowest stream gradient in the watershed and are the locations most likely to accumulate fine sediment in response to increased sediment supply. Response reaches are typically located near the mouth of the stream and reflect the cumulative effect of sediment input from all sources in the watershed. Meadow streams with silt or clay beds were avoided due to inapplicability of the sediment parameters in those streams. The minimum length of response reaches was set at 500 meters with a channel gradient less than 6 percent. The resulting pool of sample sites contains 84 watersheds that drain about 80% of total area on the Forest. The remaining 20% of the drainage area cannot be monitored with stream surveys because it is located in areas that do not have surface streams, has access limitations due to private land, or drains to very steep or intermittent stream channels.

Stratification by Managed and Reference Watersheds

Each watershed on the Forest is designated as either a managed or a reference watershed. Managed watersheds include all watersheds that do not meet the criteria for reference streams. Reference streams are located in watersheds with the least amount of human influence and represent the natural range of conditions resulting from environmental variation. Reference watersheds are used to define desired conditions and serve as benchmarks to measure effects in managed watersheds.

The criteria used to select reference watersheds followed the SWAMP guidance for establishing and managing reference streams (Ode 2009). Watersheds are considered a candidate reference if they meet the criteria in Table 2. Candidate reference streams that meet these criteria were validated using field observations and best professional judgment. A total of 20 reference streams were identified. Of these, 11 are considered near-pristine because they have no roads and most are located in wilderness areas. Most of the reference watersheds have a history of disturbance by wildfire and floods that are important components of natural variability. The most recent flood of significance was in 2006 which was approximately a 25 year event at the Salmon River gauge and a 15 year event at the Scott River gauge. Reference streams are well distributed across the Forest except for the east side (Goosenest District) where no streams met the minimum criteria. The characteristics of the reference watersheds have a

similar range as managed streams, and are representative of the background condition of the managed watersheds (Table 3).

TABLE 2. Reference watershed criteria

Disturbance	Criteria
Road density	Less than 0.19 km/km ² (0.30 mi/mi ²) with no significant road failures.
Grazing	Less than 10% of the drainage area grazed, and no BMP violations. Most have no grazing.
Mining	No significant sediment input or point sources (metals or pH). Most have only prospects.
Timber harvest	A road density of less than 0.19 km/km ² is used as surrogate for past harvest intensity.
Wildfire and other natural disturbances	Wildfire is included unless there has been substantial disturbance by suppression activities.

TABLE 3. Characteristics of reference and managed watersheds.
(Not all of the managed streams have been surveyed yet)

Watershed Characteristics	Reference Streams (n = 20)			Managed Streams (n = 64)		
	Average	Maximum	Minimum	Average	Maximum	Minimum
Drainage Area (km ²)	71	299	13	65	272	12
Mean Elevation (m)	1438	1754	1161	1324	1946	760
Maximum Elevation (m)	2179	2715	1811	2094	2715	1286
Minimum Elevation (m)	716	1296	349	652	1792	232
Precipitation (Mean Annual) (in)	73	100	53	55	87	29
Road Density (km/km ²)	0.03	0.19	0.00	1.64	3.58	0.14
Sandy geology (% of drainage area)	44	95	13	48	100	0
Channel Gradient (%)	3.5	6.5	1.1	3.0	5.9	0.3
Reach Length (m)	609	843	405	731	1622	457

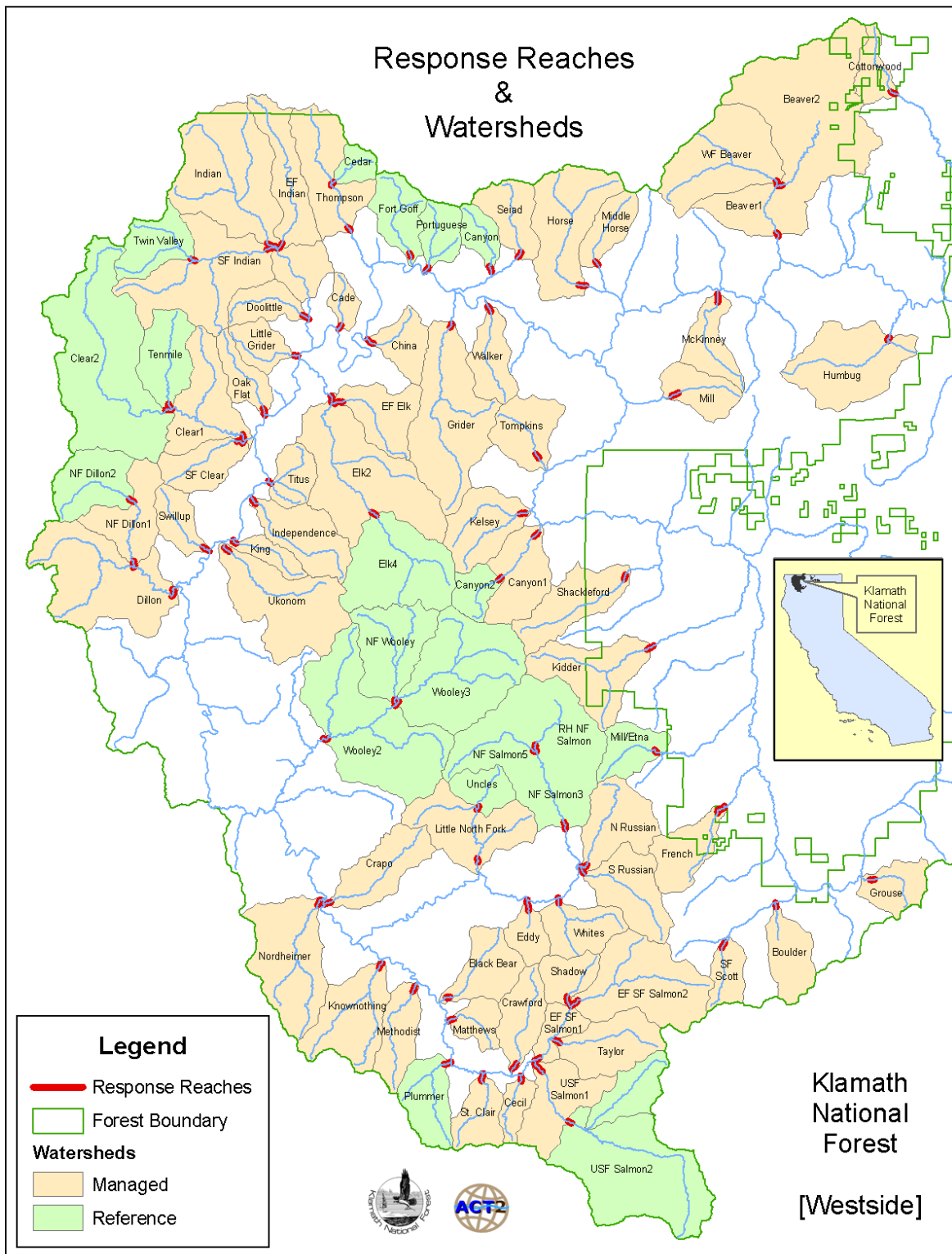


Figure 1a. Monitoring watersheds and response reaches for sediment, Westside.

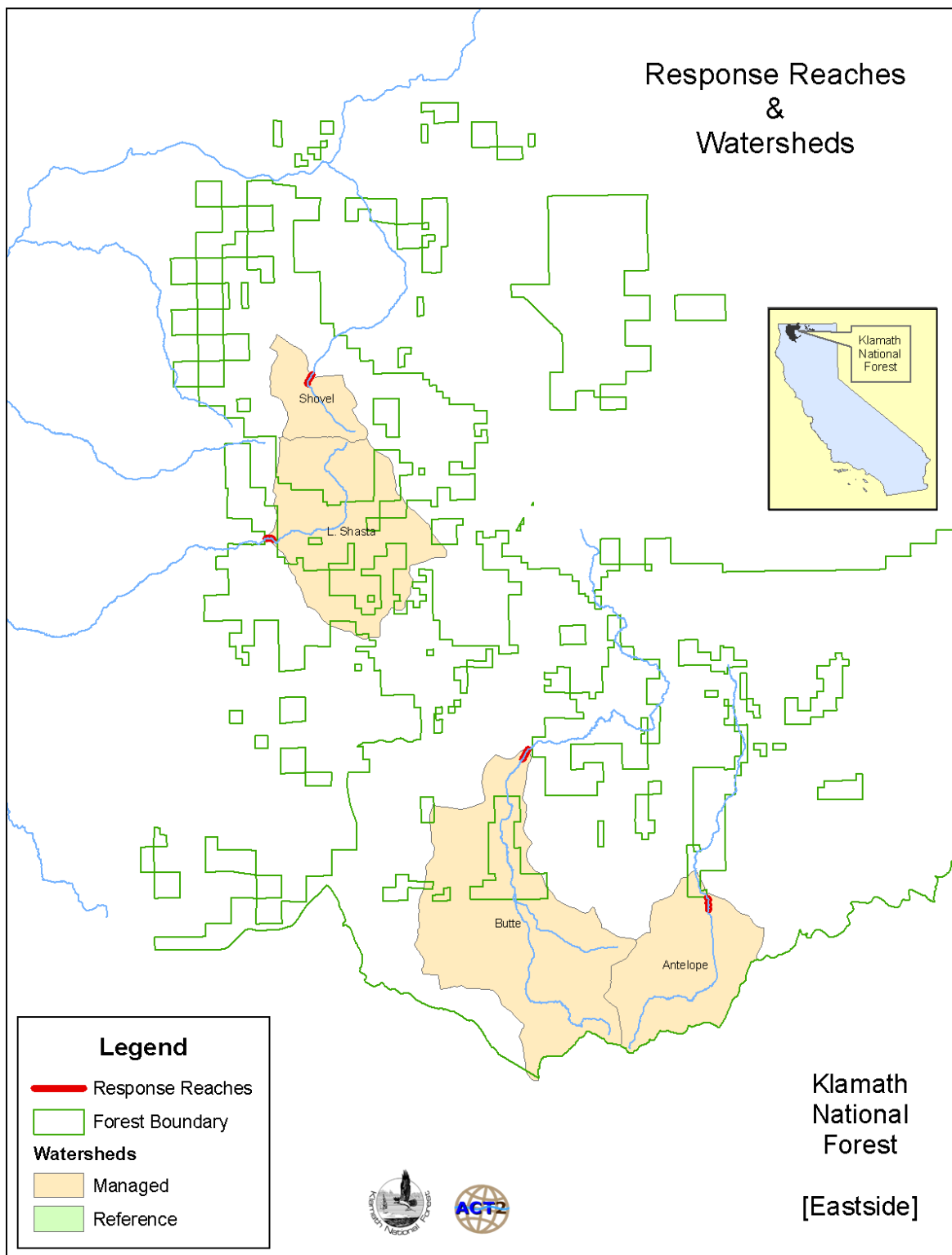


Figure 1b. Monitoring watersheds and response reaches for sediment, Eastside.

Land Use and Sediment Supply

Watershed disturbance from past management activities and natural events were modeled using three models that are commonly used to assess the cumulative effects of proposed management activities under the National Environmental Policy Act (NEPA). The U.S. Forest Service Equivalent Roaded Area (ERA) model predicts the potential for adverse effects to beneficial uses resulting from changes in watershed hydrology and sedimentation rates (USFS 1990). The model uses coefficients to weight different management activities relative to the effects of a road in terms of altering runoff per unit area of disturbance. The model output is expressed as equivalent roaded acres as a percent of drainage area. Recovery of a disturbed site is modeled by reducing the coefficients over time until ERA returns to the natural undisturbed state.

The other two models used to assess watershed disturbance are the GEO and USLE models (USFS 2004). The GEO and USLE models predict changes in sediment supply from forest management activities such as roads and timber harvest, and from natural disturbances such as wildfire. The GEO model estimates the volume of sediment delivered to the stream channel network from mass wasting processes from a 10 year storm event (de la Fuente and Haessig 1994). The USLE model estimates chronic sediment delivery from surface erosion from a 2-year 6-hour storm using the universal soil loss equation calibrated with data from local erosion plots (Laurent 2001).

The ERA, USLE, and GEO models all identify a “threshold of concern”, or inference point where the risk of adverse impacts to in-stream beneficial uses becomes a cause for concern. The current model thresholds are based on professional judgment and have not been linked to actual impacts to beneficial uses.

Natural Watershed Sensitivity

The natural sensitivity is described using geomorphic and climactic factors that influence the response of in-channel sediment to land use. The following attributes are calculated for each watershed.

Stream power index (SPI) is the product of channel slope and the calculated peak stream flow having a 2-year recurrence interval (Waananen 1977). A similar index was used by Cover (2008) who found that sediment supply scaled to stream power helped explain variations in riffle-surface sediment and V^* . The index is an indicator of the energy available to transport sediment and controls for differences in transport capacity between streams. Streams with a low stream power index have less transport capacity and are more likely to deposit fine sediment on the stream bed.

Percent Sandy Geology. Each watershed is stratified by the ability of the dominant parent material to produce sand-sized sediment. This stratification is based on criteria from Lisle and Hilton (1999) who found that V^* varies with the size of the sediment particles eroded from different parent materials. The chief determining criteria is the relative abundance of silica (SiO_2) in the bedrock (Table 4). Silica-rich rocks typically erode to produce a relatively high percentage of sand-sized particles, while silica-poor rocks generate higher percentages of silt and clay-sized sediments. Differences between watersheds are quantified by the percentage of the drainage area underlain by sand-producing parent material (silicic bedrock map units plus geomorphic landforms).

TABLE 4. Bedrock units used to stratify watersheds into sandy and non-sandy geologies.

Bedrock units producing abundant SAND	Bedrock units producing modest or little SAND
Granitic rocks, quartz-bearing schistose rocks, shale, siltstone, sandstone (greywacke), conglomerate, chert, quartzite, diorite, unconsolidated materials (e.g., glacial deposits, stream terraces, outwash deposits), tuff, pyroclastic rocks, cinders, rhyolite, rhyodacite, pumice	Slate, gabbro, undifferentiated metamorphic, undifferentiated metasediments, mudstone, ultramafic rocks, limestone, mélange units, undifferentiated volcanic rocks (including basalt, andesite, dacite), undifferentiated metavolcanic rocks

Hydrologic Response Potential is defined as the percent of the watershed in the rain on snow zone between 3,500 and 5,000 feet elevation. This factor is used in the ERA model to set the threshold of concern (USFS 2004).

Slope Stability is the inherent sensitivity of the watershed to landsliding (USFS 2004). Slope Stability is computed by running the GEO landslide model on watersheds to estimate the background landslide volume assuming no human disturbance (yd³/acre/decade). This factor is used in the ERA model to set the threshold of concern (USFS 2004).

Surface Soil Erodibility is the inherent sensitivity of a soil to surface erosion (USFS 2004). Soil erodibility is computed by running the USLE model to estimate the background surface erosion volume assuming no human disturbance (yd³/acre/decade). This factor is used in the ERA model to set the threshold of concern (USFS 2004).

TABLE 5. Site characteristics and field data for streams surveyed in 2009 to 2011. Bold sediment indicators are greater than reference conditions.

Stream	Year	Site Characteristics					Roads		Sediment Volume		In-Stream Sediment Indicators			
		Managed (M) or Reference (R)	Drainage Area (km ²)	Channel Slope	Stream Power Index (slope x Q ₂)	% of Drainage w/Sandy Geology	Road Density (km/km ²)	Equivalent Roaded Area (%)	Sediment Supply USLE (m ³ /km ² /yr)	Sediment Supply GEO (m ³ /km ² /yr)	V*	Surface Fines <2mm (%)	Subsurface Fines <6.35mm (%)	Subsurface Fines <0.85mm (%)
Canyon/Scott 2	2009	R	18.9	0.041	0.40	39	0.13	0.6	6	37	0.112	3.2	42.8	10.9
Cedar	2009	R	12.5	0.051	0.41	23	0.00	0.0	6	41	0.090	2.4	40.0	15.2
Elk 4	2009	R	82.9	0.024	0.93	76	0.00	3.1	13	107	0.121	4.2	61.6	20.8
Fort Goff	2009	R	32.8	0.038	0.73	82	0.01	1.6	4	75	0.094	2.2	51.1	19.6
Mill/Etna	2009	R	25.3	0.055	0.46	30	0.06	0.1	6	40	0.032	2.1	32.8	10.3
Portuguese	2009	R	22.6	0.033	0.44	88	0.06	1.9	5	54	0.074	2.5	45.6	12.7
Twin Valley	2009	R	35.5	0.053	1.44	22	0.00	0.0	12	33	0.054	1.2	30.1	7.8
Uncles	2009	R	21.2	0.065	0.67	54	0.00	4.7	10	114	0.111	7.2	47.0	19.9
Up. S.F. Salmon 2	2009	R	156.4	0.011	0.37	95	0.19	1.8	10	66	0.050	5.0	41.6	15.9
Canyon Seiad	2010	R	17.2	0.052	0.49	95	0.03	2.0	5	63	0.092	3.5	38.7	12.1
Clear 2	2010	R	159.5	0.015	1.40	19	0.00	0.0	9	42	0.029	3.3	*	*
NF Dillon 2	2010	R	44.1	0.028	0.97	26	0.15	1.5	12	59	0.030	2.0	28.7	6.8
NF Salmon 3	2010	R	146.2	0.018	1.05	15	0.04	0.0	7	33	0.044	0.4	32.9	10.1
NF Salmon 5	2010	R	47.5	0.020	0.43	32	0.00	0.1	9	33	0.077	12.1	29.4	8.3
NF Wooley 1	2010	R	57.0	0.058	1.62	46	0.00	1.7	10	59	0.069	7.5	29.8	8.0
Plummer	2010	R	37.1	0.035	0.51	13	0.00	0.0	8	41	0.035	0.6	29.5	8.6
Right Hand NF Salmon	2010	R	51.5	0.030	0.56	13	0.00	0.0	7	34	0.051	1.6	32.9	12.4
Tenmile	2010	R	40.7	0.031	0.83	50	0.00	0.6	10	94	0.026	3.6	38.4	10.3
Wooley 2	2010	R	299.4	0.025	2.85	40	0.02	1.4	9	56	0.030	2.9	34.2	10.8
Wooley 3	2010	R	104.7	0.026	1.31	21	0.00	0.3	7	42	0.127	6.7	33.6	11.5
Cade	2009	M	11.6	0.055	0.39	72	2.78	9.4	11	144	0.190	8.0	52.0	22.5
Clear 1	2009	M	256.1	0.005	0.78	26	0.14	0.5	9	59	0.013	1.5	28.5	9.0
Dillon	2009	M	189.1	0.013	1.70	30	0.47	4.3	14	93	0.065	0.3	28.0	7.5
Grider	2009	M	102.2	0.027	0.89	31	0.88	0.8	9	68	0.054	3.7	47.0	15.8
Little Grider	2009	M	21.4	0.030	0.43	1	1.71	2.4	22	79	0.139	5.0	46.0	16.1
Little N.F. Salmon 1	2009	M	84.3	0.027	0.91	57	0.38	4.5	10	112	0.099	3.7	43.4	13.9
Middle Horse	2009	M	24.5	0.032	0.33	100	3.58	7.9	36	99	0.246	7.9	52.2	24.5
Shackleford	2009	M	48.4	0.039	0.55	37	1.13	3.3	9	42	0.037	2.0	47.6	17.1
Thompson 2	2009	M	71.4	0.029	1.10	31	0.56	0.6	6	50	0.031	1.9	42.0	12.6
W.F. Beaver	2009	M	81.3	0.021	0.69	77	3.42	7.7	23	70	0.143	3.1	45.6	16.9
Beaver 1	2010	M	272.4	0.019	1.35	66	3.18	6.8	15	59	0.053	3.0	44.2	18.2
Beaver 2	2010	M	151.7	0.038	1.30	65	3.20	6.1	13	61	0.076	3.6	44.0	16.0
Canyon Scott 1	2010	M	63.4	0.036	0.79	32	0.66	1.4	7	54	0.053	1.8	28.6	9.5
Horse	2010	M	73.9	0.028	1.26	96	2.82	3.5	22	73	0.237	4.3	46.6	20.0
Humbug	2010	M	74.4	0.023	0.42	31	1.63	2.3	7	39	0.136	6.8	44.0	16.0
McKinney	2010	M	29.5	0.031	0.20	35	2.66	6.3	11	72	0.239	13.1	45.5	21.8
Swillup	2010	M	22.6	0.045	0.68	29	1.09	3.8	13	104	0.120	7.5	39.7	12.3

*/ No samples obtained – potential gravel patches were too shallow and/or substrate material was too large

TABLE 5 continued.

Stream	Year	Site Characteristics					Roads		Sediment Volume		In-Stream Sediment Indicators			
		Managed (M) or Reference (R)	Drainage area (km ²)	Channel slope	Stream Power Index (slope x Q ₂)	Sandy geology (% of drainage)	Road Density (km/km ²)	Equivalent Roaded Area (%)	USLE (m ³ /km ² /yr)	GEO (m ³ /km ² /yr)	V*	Surface <2mm (%)	Subsurface <6.35mm (%)	Subsurface <0.85mm (%)
Boulder	2011	M	32.8	0.022	0.16	90	1.48	1.4	12	61	0.088	8.6	47.4	23.2
China	2011	M	25.1	0.023	0.28	1	3.46	5.5	12	136	0.062	10.0	44.8	15.5
Cottonwood	2011	M	19.5	0.018	0.08	97	2.04	2.2	7	73	0.065	9.0	45.6	15.2
Crapo	2011	M	44.8	0.052	0.91	68	0.56	5.4	12	158	0.070	1.8	45.1	11.6
Crawford	2011	M	33.8	0.036	0.25	73	1.92	3.6	13	58	0.072	6.1	43.7	17.7
East Fork Elk	2011	M	39.0	0.029	0.25	3	1.98	3.7	17	63	0.068	3.1	58.6	23.4
East Fork Indian	2011	M	47.0	0.003	0.46	72	1.58	2.0	9	76	0.022	7.1	45.7	14.1
East Fork SF Salmon 1	2011	M	174.5	0.014	0.08	74	1.21	1.7	13	53	0.034	5.3	43.6	11.1
East Fork SF Salmon 2	2011	M	81.7	0.036	0.78	71	0.99	1.3	13	52	0.043	4.0	36.0	10.3
Eddy	2011	M	17.9	0.045	0.54	43	2.75	4.1	33	71	0.100	2.3	23.2	8.0
Elk 2	2011	M	233.9	0.011	0.85	51	1.06	4.0	12	106	0.138	3.9	40.6	14.5
Grouse Scott	2011	M	23.8	0.035	0.23	44	2.33	5.4	13	59	0.076	0.7	35.1	8.6
Independence	2011	M	46.4	0.031	0.74	40	0.95	5.3	11	96	0.061	4.1	44.2	12.9
Indian 3	2011	M	106.5	0.011	0.62	9	2.25	2.9	13	84	0.080	6.4	40.6	16.3
Kelsey	2011	M	45.4	0.030	0.46	38	0.72	1.5	8	86	0.076	3.4	47.1	14.3
Knownothing	2011	M	58.4	0.016	0.38	27	1.43	2.4	18	95	0.069	0.3	42.5	17.1
Matthews	2011	M	18.7	0.046	0.18	33	1.65	2.6	11	65	0.049	6.7	36.6	18.9
Methodist	2011	M	32.4	0.029	0.31	5	1.62	2.7	13	77	0.081	2.2	63.3	27.8
Mill Creek Scott	2011	M	29.2	0.035	0.29	10	2.79	4.9	16	84	0.070	3.2	54.2	17.7
Nordheimer	2011	M	80.2	0.010	0.32	21	0.20	0.2	6	88	0.044	2.6	34.4	10.6
North Russian	2011	M	47.1	0.017	0.22	34	1.18	2.4	13	63	0.094	4.3	54.1	18.4
Oak Flat	2011	M	22.8	0.039	0.52	1	0.96	1.5	11	44	0.103	3.8	50.8	17.0
South Fork Clear	2011	M	30.2	0.027	0.51	12	1.46	2.2	9	76	0.028	1.4	35.0	8.8
South Fork Indian	2011	M	128.7	0.010	0.72	17	1.04	1.7	11	60	0.099	9.3	40.7	17.4
South Fork Scott 4	2011	M	18.5	0.051	0.26	65	1.95	2.6	9	125	0.095	7.0	43.4	19.0
South Russian	2011	M	47.9	0.029	0.38	89	0.86	1.3	14	48	0.029	1.2	35.2	11.6
Taylor	2011	M	47.2	0.026	0.30	74	1.39	1.2	9	49	0.092	4.7	46.4	18.0
Tompkins	2011	M	33.7	0.044	0.48	61	1.78	3.5	20	101	0.060	4.8	51.3	17.3
Ukonom	2011	M	84.4	0.027	1.13	77	0.60	3.5	12	95	0.056	4.5	46.9	13.2
Upper SF Salmon	2011	M	203.9	0.011	0.44	95	0.49	2.0	10	68	0.073	4.2	41.6	12.9
Walker	2011	M	30.6	0.045	0.48	71	2.37	3.7	22	118	0.074	2.8	35.0	6.6
Whites	2011	M	30.3	0.042	0.45	66	1.38	1.6	22	42	0.493	14.6	57.5	15.6

*/ No samples obtained – potential gravel patches were too shallow and/or substrate material was too large

RESULTS

Between 2009 and 2011 we sampled 69 streams, or 85% of all the watersheds in Figure 1. The sites included 20 reference streams and 49 managed streams. Most of the data (59 streams) were collected by the Northern California Resource Center, a non-profit organization that is independent from the Forest Service. The quality of the data is considered good with very few problems encountered during field sampling. The highest stream flow during the sampling period was 15,100 cfs at the Salmon River gauge in 2010, which is less than a 2-year flood event. The mean daily discharge in 2009 and 2010 was 1234 and 1722 ft³/sec respectively which is less than long-term mean annual flow of 1791 ft³/sec. A heavy snowpack in 2011 kept stream flows high until late in the summer, with a mean flow 2474 ft³/sec.

Survey Error

We completed 9 repeat surveys to estimate the precision of each sediment indicator. Repeat surveys included 3 pairs of successive measurements by the same crews in the same streams, and 6 pairs between different crews. Variation between successive surveys is greatest for surface sediment and least for V* (Tables 6 and 7). The standard deviation of the differences for all pairs is used to represent the total variability in the dataset (the survey error).

Reference Conditions and Natural Variability

A “reference condition” was calculated for each sediment indicator using the 75th percentile of reference values plus the survey error (Figure 2). The reference condition discriminates well between reference and managed streams and is an appropriate benchmark for measuring the effects of management (Figures 3 and 4). The reference condition includes the bulk of the reference values while excluding high values in burned watersheds such as in Elk Creek (Figure 2). Subsurface sediment in reference streams is significantly correlated with the percent of the watershed with sandy geology. However, the strength of the relation is affected by three high values in sandy watersheds that experienced recent wildfires (Elk, Uncles, and Ft. Goff).

Reference conditions are substantially different than the Regional Water Board’s desired conditions and the sediment standards in the Klamath National Forest Land and Resource Management Plan. When compared to reference streams, the state’s desired condition overestimates V* and underestimates subsurface fines (Figure 4). Only 4 out of the 20 reference streams on the KNF can attain the state values for subsurface fines <6.35mm. The Forest Plan standard of 15% is higher than the maximum value for any stream on the Forest. Neither the state nor the Forest Service standards have much utility as a benchmark for measuring management effects because they cannot detect the difference between managed and reference conditions.

Management Effects on In-stream Sediment

The cumulative effect of management on stream sediment is evaluated using a weight-of-evidence approach based on the number of indicators exceeding the reference condition, and the relative sediment supply from human-caused sources (Table 9). Of the 49 managed streams we surveyed, 27 have sediment values less than the reference condition for all four indicators (Fig.3, Table 10). Another 22 streams have sediment values greater than the reference condition for at least one indicator. To determine if human-related sediment sources could have caused the high values, the dominant sediment source in each watershed is estimated using

the Forest Service GEO and USLE models. The models show that erosion from roads and timber harvest supply >50% of the total sediment in 16 of the 22 watersheds (Table 10). In these streams human caused sediment sources appear to have caused an increase in streambed sediment and an adverse effect on beneficial uses. In 6 of the 22 watersheds with sediment greater than the reference, the models show that natural sources supply >50% of the total sediment. Natural erosion is the most likely cause of high sediment in these streams but a more detailed review of sediment source inventories is needed to determine the actual contribution from human-caused sources.

The median effect of management on all streams in the study was assessed by comparing the entire distribution of sediment values in reference and managed streams. An increase in sediment supply has shifted the overall distribution upward in the managed streams (Figure 4). Sub-surface sediment <6.35mm and sub-surface sediment <0.85mm are significantly greater in managed streams than in reference streams, but V^* and riffle-surface sediment are not (Mann-Whitney test at $\alpha=0.05$). Compared to reference streams, management has increased the median subsurface sediment <6.5mm by 10% and subsurface sediment <0.85mm by 5%.

Thresholds for Cumulative Watershed Effects Models

A multiple linear regression similar to the one done by Cover (2008) was developed to relate forest management and natural watershed sensitivity to in-channel sediment conditions. Equivalent roaded area and the sediment volumes predicted by the USLE and GEO models are used as predictor variables, with V^* , sub-surface sediment, and riffle-surface sediment as the response variables. The USLE and GEO sediment volumes were log-transformed to meet the assumptions for linear regression. Watershed sensitivity attributes were added as predictor variables if they improved the fit of the model.

The results show that all four indicators of in-channel sediment have a significant positive correlation with the watershed disturbance estimated by the equivalent roaded area, USLE, and GEO models (Table 11, Figures 5, 6, 7). Stream power had a significant negative correlation with all four sediment indicators and it improved all of the correlations between stream sediment and ERA, GEO, or USLE when added as a predictor variable. The percent of the watershed with sandy geology significantly improved the correlations for V^* and subsurface sediment <6.35mm, but not riffle-surface sediment or subsurface sediment <0.85mm. Background slope stability, background surface erosion, and the percent of the watershed in the rain-on-snow zone did not significantly improve the correlations between in-stream sediment and ERA, GEO, or USLE. The models that include ERA have a higher coefficient of determination and are a better predictor of in-channel sediment than those that use GEO or USLE sediment supply. Although significant, the correlations are very weak ($r^2 = 0.46$ to 0.08) with the weakest correlations for riffle-surface sediment.

Thresholds for equivalent roaded area and sediment supply can be identified where the regression models predict attainment of the reference condition for in-stream sediment. Stream power and percent sandy geology have a strong influence on the ERA threshold, with thresholds in the most sensitive watersheds over 8 times those in the least sensitive watersheds (Figure 8). However, the accuracy of the predicted sediment is very low. Plots of the predicted versus measured sediment show a poor fit with the 1:1 line (Figure 9), with Nash-Sutcliffe Efficiencies (NSE) between 0.10 and 0.48 (Table 11). Generally, models can be judged as unsatisfactory if the NSE is <0.50 (Moriassi 2007).

SUMMARY AND CONCLUSIONS

Sediment monitoring conducted between 2009 and 2011 shows that most streams on the Klamath National Forest have no evidence of alteration by human-caused sediment sources (Figure 10). Streambed sediment was measured in 69 watersheds representing most of major streams on the Forest. Reference conditions were developed from 20 minimally disturbed watersheds for V^* , riffle surface sediment $<2\text{mm}$, subsurface sediment $<6.35\text{mm}$, and subsurface sediment $<0.85\text{mm}$. When compared to the reference condition, in-stream sediment in managed streams is less than the reference for all four indicators in 27 of the 49 managed watersheds in our survey. Although some of these watersheds have been heavily managed there is no evidence that in-stream sediment has been altered or that beneficial uses have been adversely affected. We conclude that the desired conditions for sediment are fully attained in these streams.

The monitoring program identified a group of watersheds where human-caused sediment sources have had a measurable cumulative impact on in-stream sediment. In-stream sediment is greater than the reference condition for at least one indicator in 22 of the 49 managed watersheds in our survey. Of these, human-caused sources are the dominant source of sediment in 16 streams. We conclude that these 16 streams have cumulative in-stream impacts due to human-caused sediment sources and are not attaining desired conditions for riparian reserves. In the other 6 streams natural disturbances such as wildfire are the dominant sediment source and are the likely cause of high in-channel sediment. The streams with altered sediment conditions do not necessarily reflect a lack of BMP effectiveness because much of the human-caused sediment is from land uses that predate modern BMPs. For example, some watersheds contain legacy sites associated with roads that were built along stream channels before there were restrictions on development in riparian areas. Altered sediment conditions do reflect compliance with State water quality regulations because successful restoration of legacy sites is required for TMDL compliance.

Our analysis establishes a link between watershed disturbance and the amount of fine sediment deposited on the streambed. We found significant correlations between equivalent roaded area and indicators of in-stream sediment including V^* , riffle-surface sediment, subsurface sediment $<6.35\text{mm}$, and subsurface sediment $<0.85\text{mm}$. The sediment yields estimated by the GEO mass wasting model and the USLE surface erosion model were also significantly correlated with the four indicators of in-stream sediment. The strongest correlations have ERA, stream power, and percent sandy geology as a predictor of V^* ($R^2 = 0.44$), and ERA and stream power as a predictor of subsurface sediment $<0.85\text{mm}$ ($R^2 = 0.46$). All other models have an R^2 between 0.34 and 0.08. The correlations for V^* are similar to those found by Lisle (1999) and Sable and Wohl (2006). Our linkages are much weaker than those of Cover (2008), probably because our dataset covers the entire Klamath National Forest and includes watersheds with a wider range of background characteristics and disturbance histories. Watersheds reported by Cover (2008) were all underlain by bedrock producing high percentages of sandy material.

We confirmed that naturally sensitive watersheds can tolerate less disturbance than watersheds with a low sensitivity without affecting beneficial uses. The sensitivity factors of stream power and the percent of the drainage underlain by sandy parent material significantly affected the correlation between ERA and in-stream sediment. Watersheds with low stream-power and sandy geology could tolerate about one-eighth as much equivalent roaded area as watersheds with high stream power and non-sandy geology without exceeding the reference condition for V^* . Sandy geology influenced V^* and subsurface sediment $<6.35\text{mm}$, but not riffle-surface sediment or subsurface sediment $<0.85\text{mm}$. This result is expected because sediment $<0.85\text{mm}$

excludes the very coarse sand and fine gravel produced by sandy geologies. Some attributes of watershed sensitivity that are commonly thought to be important showed no significant correlation with in-stream sediment. Background slope stability, highly erodible soils, and the percent of the drainage in the rain-on-snow zone are expected to influence in-channel sediment during major floods, but had no correlation during the relatively flood-free period of this study.

The regression equations could be used to establish a new threshold of concern for the equivalent roaded area, GEO, and USLE models. Thresholds could be set where the regression models predict attainment of the reference condition for in-stream sediment, or at some other level where the risk of cumulative impacts on beneficial uses becomes unacceptable. However, the regression models are not accurate enough to predict streambed sediment with certainty. The predicted stream sediment is only a coarse approximation of the cumulative stream response to disturbance during periods with no floods. If the regressions are used to set new thresholds, the equation for V^* predicted by ERA should be used because it has the strongest correlation and includes geology as a contributing factor.

In-channel sediment in non-sandy watersheds responded to increased sediment supply at a similar rate as in sandy watersheds. This may contradict Lisle (1999) who found that V^* did not respond to increasing sediment yield in channels draining fines-poor lithologies. Our analysis shows that V^* can be used as a method to measure the in-channel effects of increasing sediment supply from non-granitic watersheds.

TABLE 6. Variability of sediment indicators for pairs of repeat surveys at the same site (survey error). Pairs are either within the same crew or between different crews. The “survey error” is the standard deviation of the differences.

Stream Name	Year Surveyed	Pair	V* (%)			Surface Sediment (%)			SubSurface <6.35mm (%)			SubSurface <0.85mm (%)		
			Crew 1	Crew 2	Difference	Crew 1	Crew 2	Difference	Crew 1	Crew 2	Difference	Crew 1	Crew 2	Difference
Plummer	2010	within	0.032	0.037	-0.005	0.4	0.7	-0.30	26.3	32.6	-6.30	6.9	10.2	-3.30
Tennile	2010	within	0.027	0.025	0.002	4.0	3.1	0.90	42.2	34.6	7.60	12.1	8.4	3.70
Swillup	2010	within	0.129	0.111	0.018	10.5	4.5	6.00	35.9	43.5	-7.60	10.2	14.3	-4.10
Beaver 2	2010	between	0.073	0.079	-0.006	2.6	4.5	-1.90	43.1	44.9	-1.80	14.0	17.9	-3.90
Canyon Scott 1	2010	between	0.056	0.049	0.007	0.5	3.1	-2.60	27.9	29.2	-1.30	10.6	8.3	2.30
Humbug 1	2010	between	0.165	0.107	0.058	8.5	5.1	3.40	41.0	47.0	-6.00	14.3	17.6	-3.30
Grider (Crews A – B)	2009	between	0.046	0.056	-0.010	4.8	2.7	2.10	42.4	45.6	-3.20	14.7	15.3	-0.60
Grider (Crews B – C)	2009	between	0.056	0.060	-0.004	2.7	3.6	-0.90	45.6	53	-7.40	15.3	17.4	-2.10
Grider (Crews C – A)	2009	between	0.060	0.046	0.014	3.6	4.8	-1.20	53	42.4	10.60	17.4	14.7	2.70
Mean Difference					0.008			0.61			-1.71			-0.96
Coeff. of Variation					2.625			4.57			3.85			3.22
Standard Deviation of Differences					0.021			2.79			6.59			3.09

TABLE 7. Summary statistics for natural sediment conditions in reference streams.

	Pool Sediment (V*)	Surface Sediment <2mm (%)	Sub-Surface Sediment <6.35mm (%)	Sub-Surface Sediment <0.85mm (%)
N	20	20	19	19
Mean	0.067	3.7	37.9	12.2
Maximum	0.127	12.1	61.6	20.8
Minimum	0.026	0.4	28.7	6.8
Standard Deviation	0.034	2.8	8.8	4.2
Coefficient of Variation	0.51	0.76	0.23	0.34
75 th Percentile	0.0935	4.8	42.8	15.2
Reference Condition = 75th percentile + Survey Error	0.115	7.6	49.4	18.3

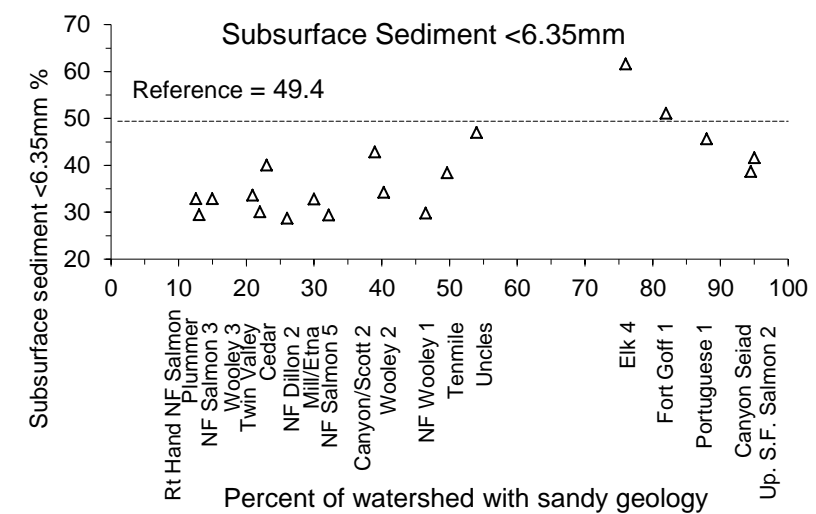
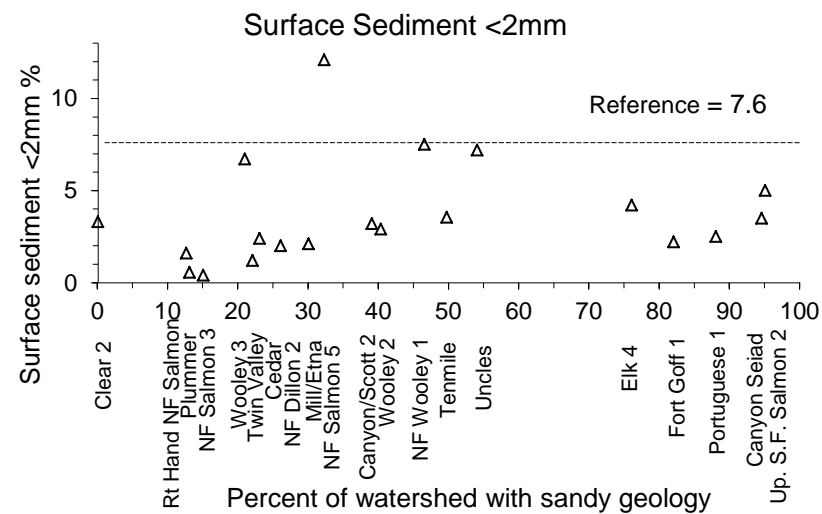
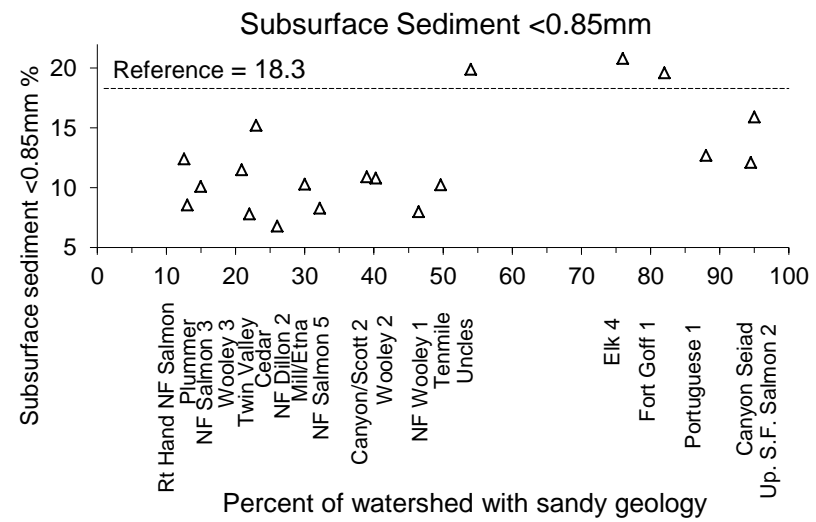
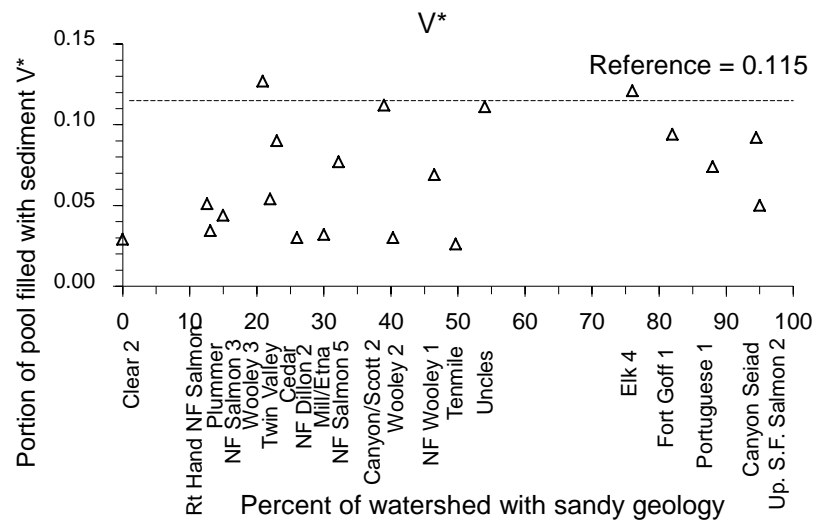


Figure 2. Sediment indicators and the in reference streams.

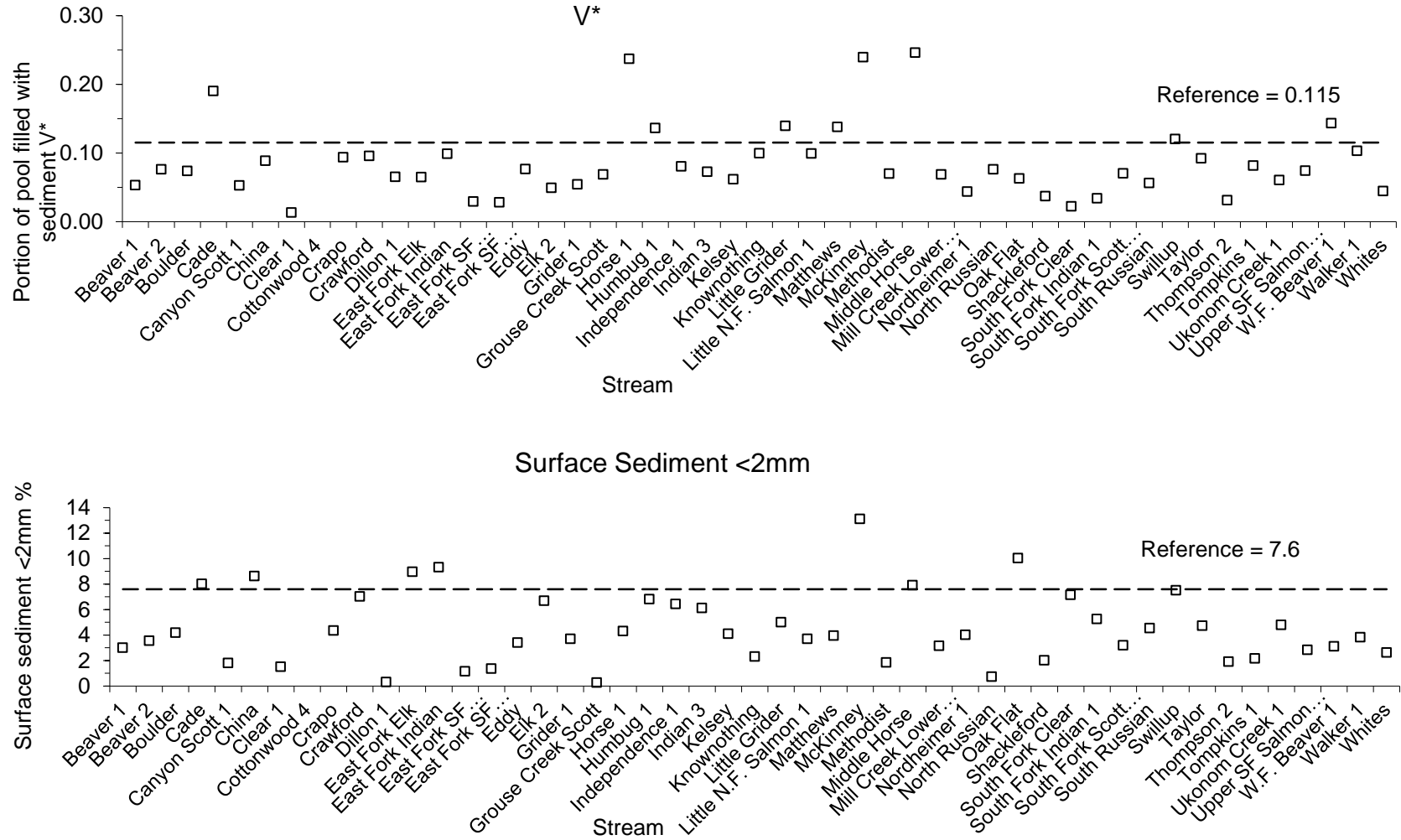


Figure 3. Sediment indicators in managed streams. Note that Cottonwood Creek's V^* of 0.48 is off the chart.

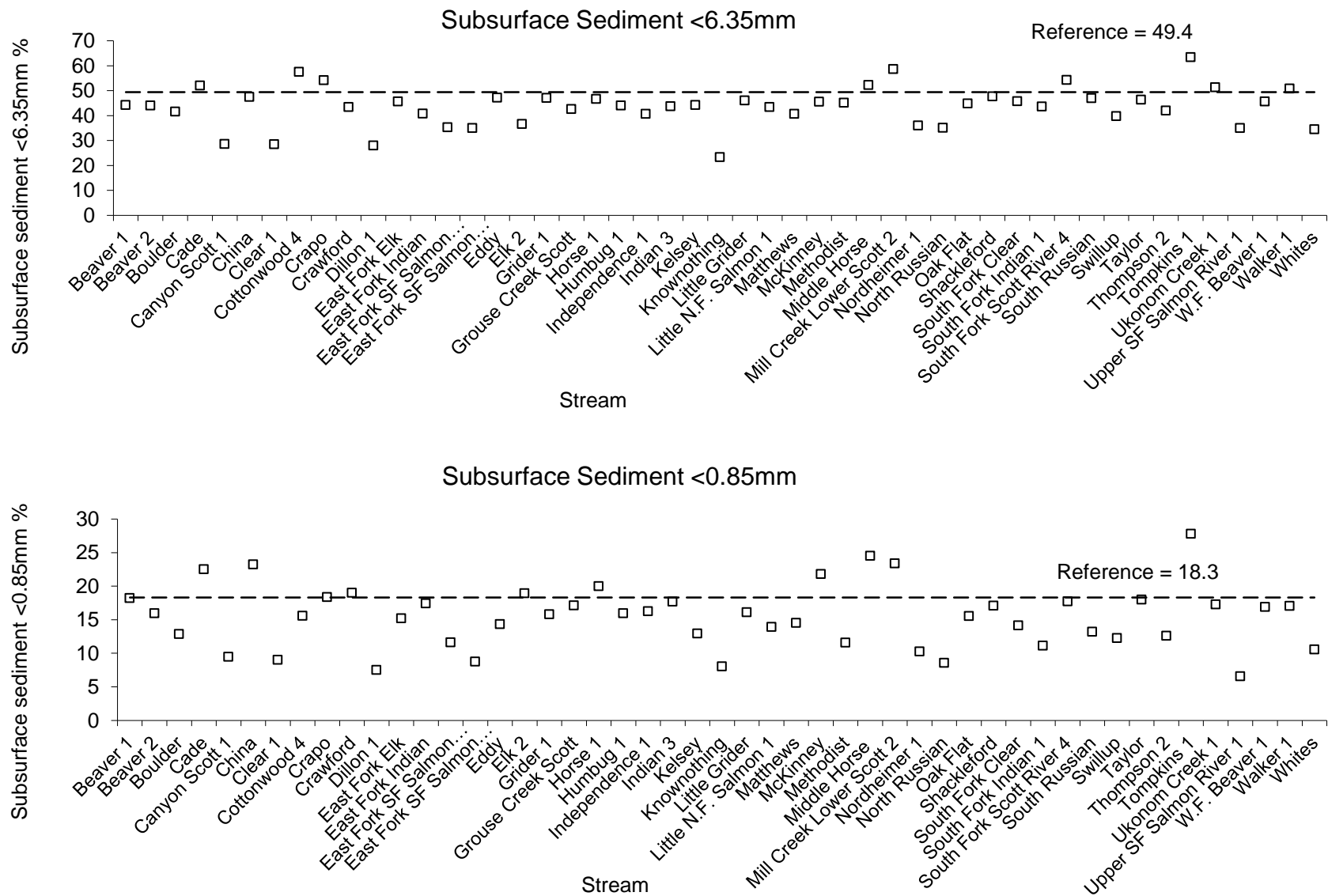
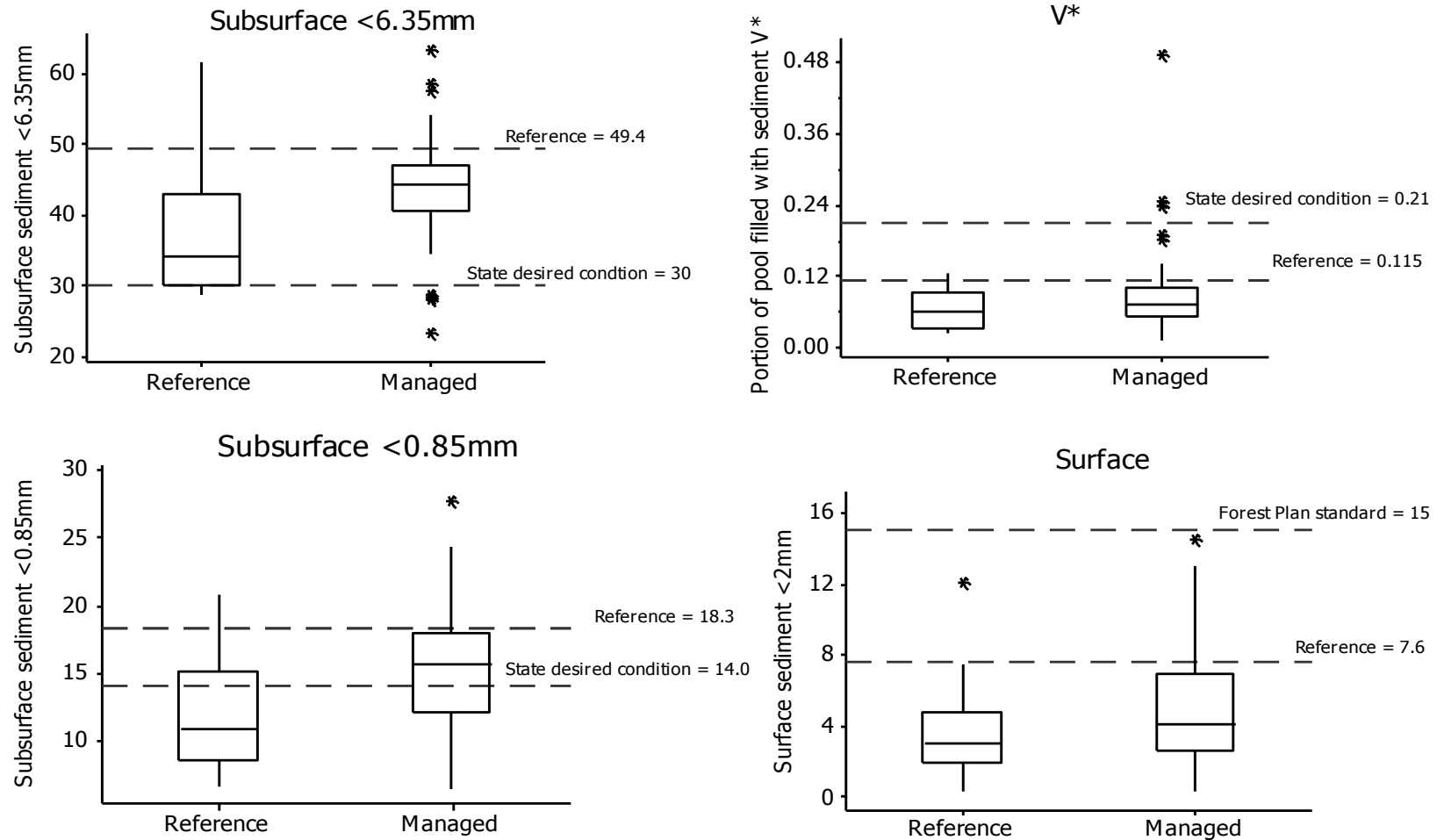


Figure 3 Continued. Sediment indicators in managed streams.



Boxes are median and quartiles (75th and 25th percentiles). Outliers are $> Q3 + 1.5 (Q3 - Q1)$ and $< Q1 - (Q3 - Q1)$

Figure 4. Comparison of sediment in managed streams with reference streams, desired conditions from the North Coast Regional Water Board, and standards from the KNF land management plan. Mann-Whitney tests at $\alpha=0.05$ show that the managed and reference medians for V^* and riffle-surface sediment are not significantly different, but sub-surface sediment $<6.35\text{mm}$ and $<0.85\text{mm}$ are.

TABLE 8. Proposed interpretation of adverse effects due to human-caused sediment sources. The dominant sediment source is determined from either the USLE or the GEO models (Table 11), or from field surveys of sediment sources.

Effects (Number of indicators >reference condition)	Dominant sediment source	Beneficial use support	Interpretation
1 to 4	Human-caused sources supply >50% of the total sediment	Not Supporting	Adverse effects. Human-related sediment sources are the likely cause
1 to 2	Human-caused sources supply <50% of the total sediment	Partially Supporting	Beneficial uses may have been affected but it is not clear if human sources are the cause.
1 to 4	Natural sources supply $\geq 99\%$ of the total sediment	Supporting	No substantial human-related sediment sources.
0	Any		No adverse effects

TABLE 9. Managed streams attaining and not attaining reference conditions.

Watersheds	V*		% Surface <2mm		% Sub-Surface <6.35mm		% Sub-Surface <0.85mm		Total # of Indicators >Reference
	> Reference	< Reference	> Reference	< Reference	> Reference	< Reference	> Reference	< Reference	
Cade	X		X		X		X		4
Middle Horse	X		X		X		X		4
McKinney	X		X			X	X		3
Cottonwood	X		X		X			X	3
China		X	X			X	X		2
Mill Creek Scott		X		X	X		X		2
Tompkins		X		X	X		X		2
Horse	X			X		X	X		2
East Fork Elk		X	X			X		X	1
Matthews	X			X		X		X	1
South Fork Scott River		X		X	X			X	1
Walker		X		X	X			X	1
Crawford		X		X		X	X		1
Little Grider	X			X		X		X	1
W.F. Beaver	X			X		X		X	1
Humbug	X			X		X		X	1
Swillup	X			X		X		X	1
Crapo		X		X	X		X		2
Oak Flat		X	X			X		X	1
Elk 2		X		X		X	X		1
East Fork Indian		X	X			X		X	1
Ukonon		X		X	X			X	1
Beaver 1		X		X		X		X	0
Beaver 2		X		X		X		X	0
Boulder		X		X		X		X	0
Canyon Scott		X		X		X		X	0
Clear 1		X		X		X		X	0
Dillon		X		X		X		X	0
East Fork SF Salmon 1		X		X		X		X	0
East Fork SF Salmon 2		X		X		X		X	0
Eddy		X		X		X		X	0

Grider		X		X		X		X		0
Grouse Creek Scott		X		X		X		X		0
Independence		X		X		X		X		0
Indian 3		X		X		X		X		0
Kelsey		X		X		X		X		0
Knownothing		X		X		X		X		0
Little N.F. Salmon 1		X		X		X		X		0
Methodist		X		X		X		X		0
Nordheimer		X		X		X		X		0
North Russian		X		X		X		X		0
Shackleford		X		X		X		X		0
South Fork Clear		X		X		X		X		0
South Fork Indian		X		X		X		X		0
South Russian		X		X		X		X		0
Taylor		X		X		X		X		0
Thompson		X		X		X		X		0
Upper SF Salmon River		X		X		X		X		0
Whites		X		X		X		X		0
Total number of streams:	11	40	10	41	10	41	10	41		

TABLE 10. Sediment sources estimated from the GEO and USLE models for watersheds exceeding the reference condition for in-stream sediment. The harvest category includes a range of vegetation disturbances.

Watershed	Background (% of total)		Fire (% of total)		Harvest (% of total)		Roads (% of total)	
	USLE	GEO	USLE	GEO	USLE	GEO	USLE	GEO
Cade	37	34	0	28	2	2	61	36
Middle Horse	16	46	0	0	2	7	83	47
McKinney	21	46	0	0	0	7	79	47
Horse 1	30	62	0	2	0	7	70	29
Little Grider	19	58	0	1	0	3	81	39
W.F. Beaver 1	14	76	0	0	1	5	85	19
Humbug	38	57	0	0	2	0	61	43
Swillup	58	58	0	24	0	0	42	17
Cottonwood	38	38	0	0	0	16	62	46
China	30	38	0	10	8	4	62	48
Mill Creek Scott	18	39	0	0	0	1	82	60
Tompkins	29	40	0	11	0	13	71	36
Crapo	58	23	29	69	0	3	14	5
Oak Flat	50	67	2	1	0	2	48	30
East Fork Elk	31	45	0	20	0	4	69	32
Matthews	34	51	0	0	9	1	57	48
Elk 2	58	33	17	52	0	2	26	13
South Fork Scott River	37	41	0	0	0	10	63	49
Walker	35	45	0	5	11	14	54	37
East Fork Indian	66	42	0	24	0	1	34	33
Crawford	30	59	0	4	16	0	54	36
Ukonom	59	44	25	45	0	3	16	9
<i>Reference Streams</i>								
Elk 4	76	34	24	66	0	0	0	0
Ft. Goff 1	99	61	0	39	1	0	0	0
Uncles	86	31	14	69	0	0	0	0
N.F. Salmon 5	99	98	1	2	0	0	0	0
Wooley 3	99	95	1	5	0	0	0	0

TABLE 11. Regression models for stream response to equivalent roaded area, GEO, and USLE modeled sediment supply.
All models are significant at $\alpha = 0.05$

Model	Equation $Y = a + b(X_1) + c(X_2)$	n	R ² (%)	RMSE	Nash-Sutcliffe Model Efficiency Coefficient (sediment predicted by regression compared to measured values)
ERA	1. Subsurface <0.85mm = $12.1 + 1.41(\text{ERA}) - 2.21(\text{SPI})$	68	45.7	3.6	0.48
	2. Subsurface <6.35mm = $37.7 + 1.66(\text{ERA}) - 4.54(\text{SPI}) + 0.0602(\% \text{Sandy})$	68	33.2	7.1	0.35
	3. $V^* = 0.0246 + 0.00543(\text{ERA}/\text{SPI}) + 0.0005539(\% \text{Sandy})$	69	44.2	0.053	0.44
	4. Surface <2mm = $3.09 + 0.202(\text{ERA}/\text{SPI})$	69	24.1	2.7	0.24
GEO	5. Subsurface <0.85mm = $-9.24 + 5.99(\ln \text{GEO}) - 2.18(\text{SPI})$	68	29.4	4.1	0.32
	6. Subsurface <6.35mm = $2.22 + 9.41(\ln \text{GEO}) - 4.33(\text{SPI}) + 0.0649(\% \text{Sandy})$	68	34.4	7.1	0.36
	7. $V^* = -0.106 + 0.0337 \ln(\text{GEO}/\text{SPI}) + 0.000632(\% \text{Sand})$	69	27.1	0.060	0.27
	8. Surface <2mm = $-2.62 + 1.46 \ln(\text{GEO}/\text{SPI})$	69	15.3	2.8	0.15
USLE	9. Subsurface <0.85mm = $8.47 + 3.20(\ln \text{USLE}) - 2.47(\text{SPI})$	68	14.6	4.5	0.16
	10. Subsurface <6.35mm = $32.9 + 3.42(\ln \text{USLE}) - 4.77(\text{SPI}) + 0.0854(\% \text{Sandy})$	68	20.3	7.8	0.23
	11. $V^* = -0.0371 + 0.0301 \ln(\text{USLE}/\text{SPI}) + 0.000696(\% \text{Sandy})$	69	24.4	0.061	0.24
	12. Surface <2mm = $0.95 + 1.15 \ln(\text{USLE}/\text{SPI})$	69	9.5	2.9	0.10
Road Density	13. Subsurface <0.85mm = $11.4 + 2.67(\text{Road Density})$	68	35.6	3.8	0.36
	14. Subsurface <6.35mm = $34.2 + 3.46(\text{Road Density}) + 0.0798(\% \text{Sandy})$	68	28.8	7.3	0.29
	15. $V^* = 0.0378 + 0.0208(\text{Road Density}) + 0.000406(\% \text{Sandy})$	69	29.0	0.042	0.08
	16. Surface <2mm = $3.51 + 0.790(\text{Road Density})$	69	7.6	2.9	0.23

Where:

USLE = Sediment supply ($\text{m}^3/\text{km}^2/\text{yr}$) predicted by the USLE model
GEO = Sediment supply ($\text{m}^3/\text{km}^2/\text{yr}$) predicted by the GEO model
ERA = Equivalent roaded area (% of watershed area)
SPI = Stream power index (Q_2/slope) of response reach
% Sandy = Percent of watershed with sandy geology
Road density = km/km^2

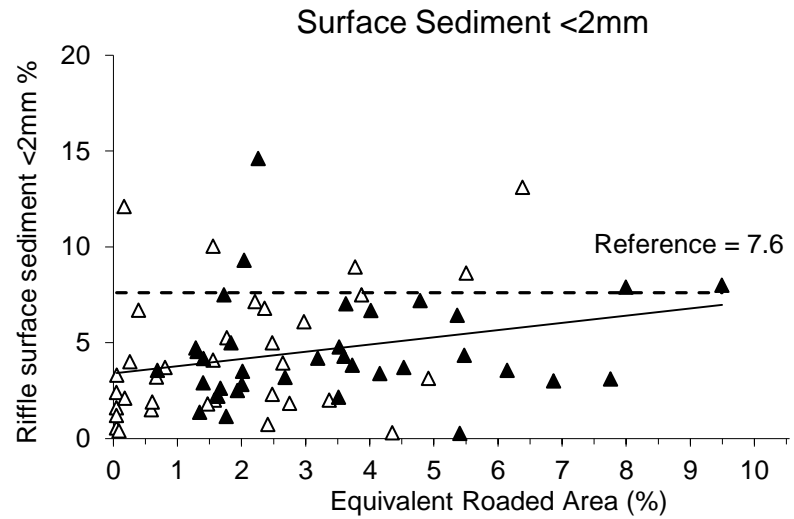
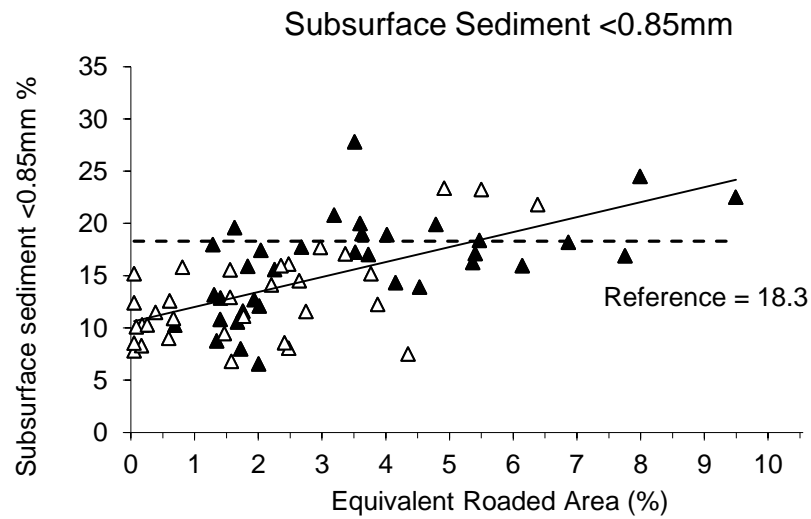
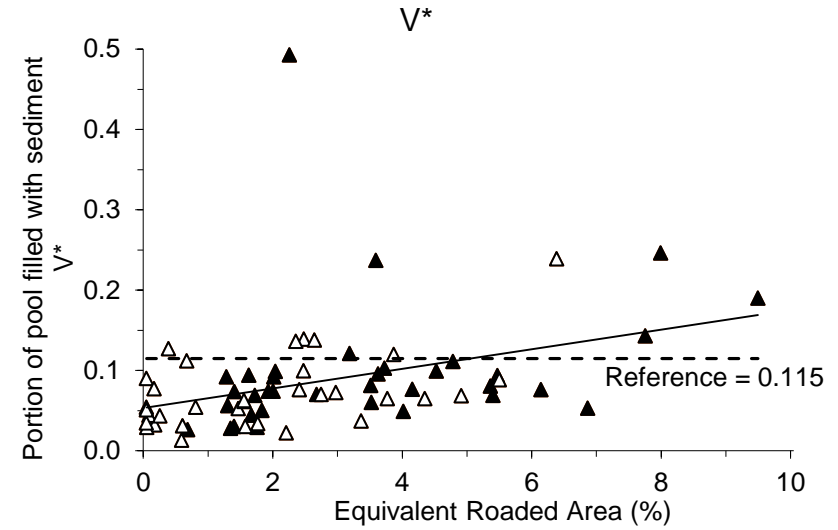
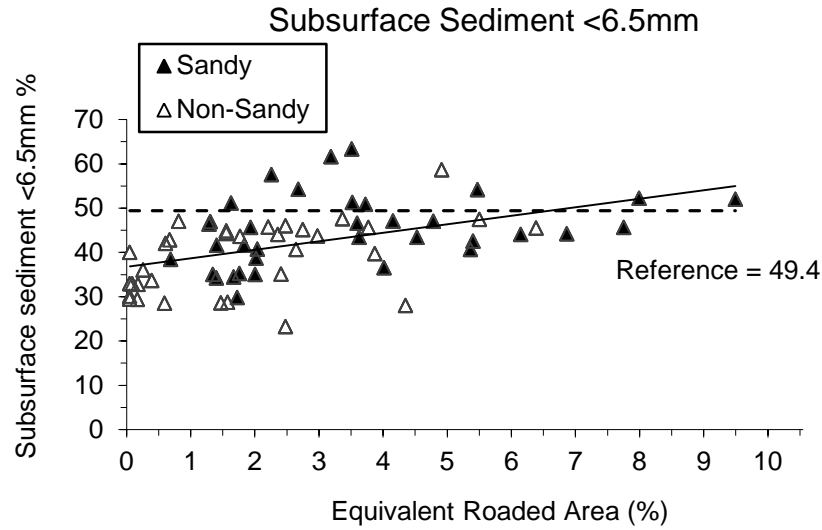


Figure 5. Stream response to equivalent roaded area. Sandy streams have >40% of their drainage area in sandy geology. The high outlier for V^* is due to a low stream power in Cottonwood Creek.

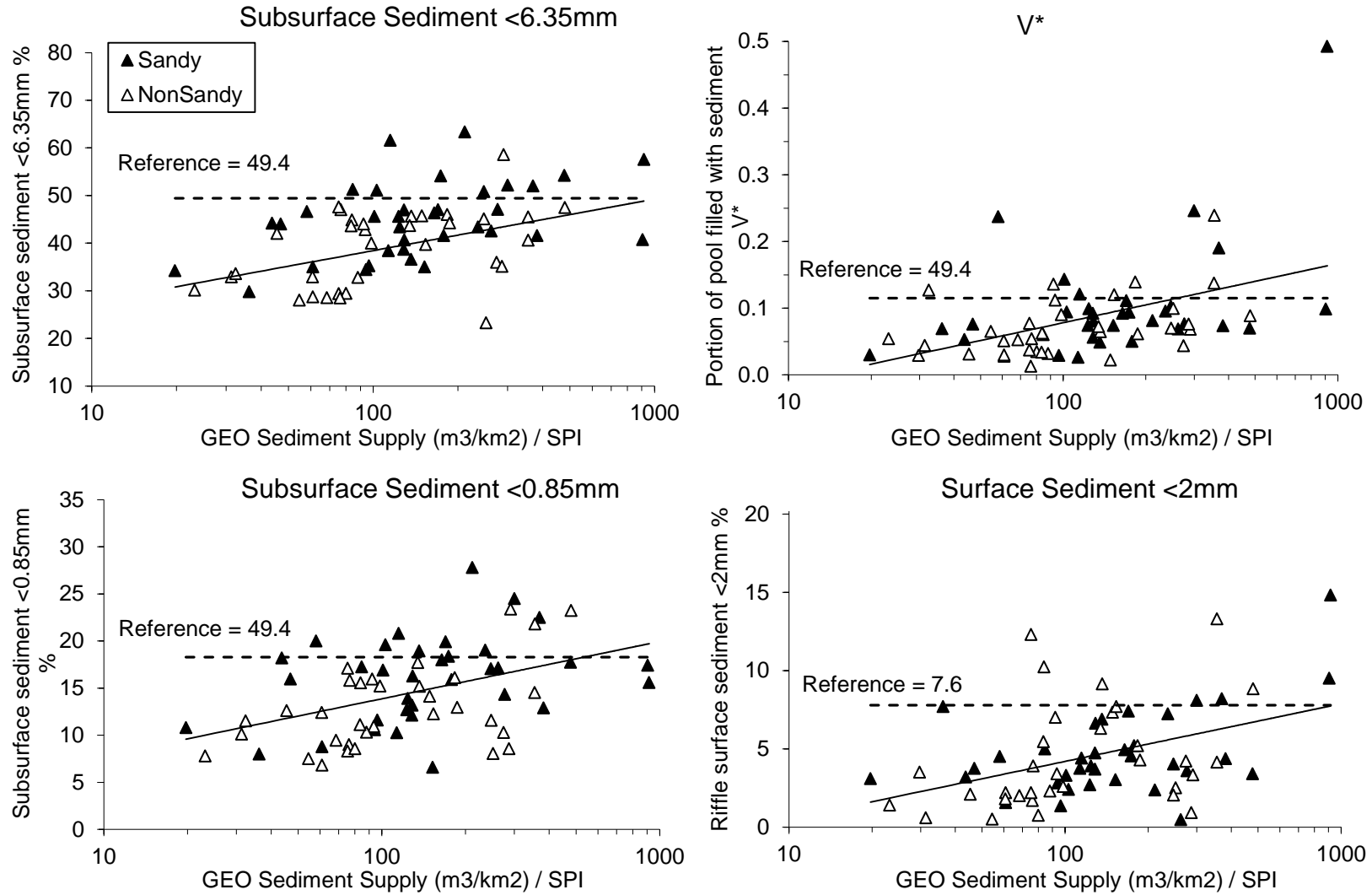


Figure 6. Stream response to GEO sediment supply. Sandy streams have >40% of their drainage area in sandy geology.

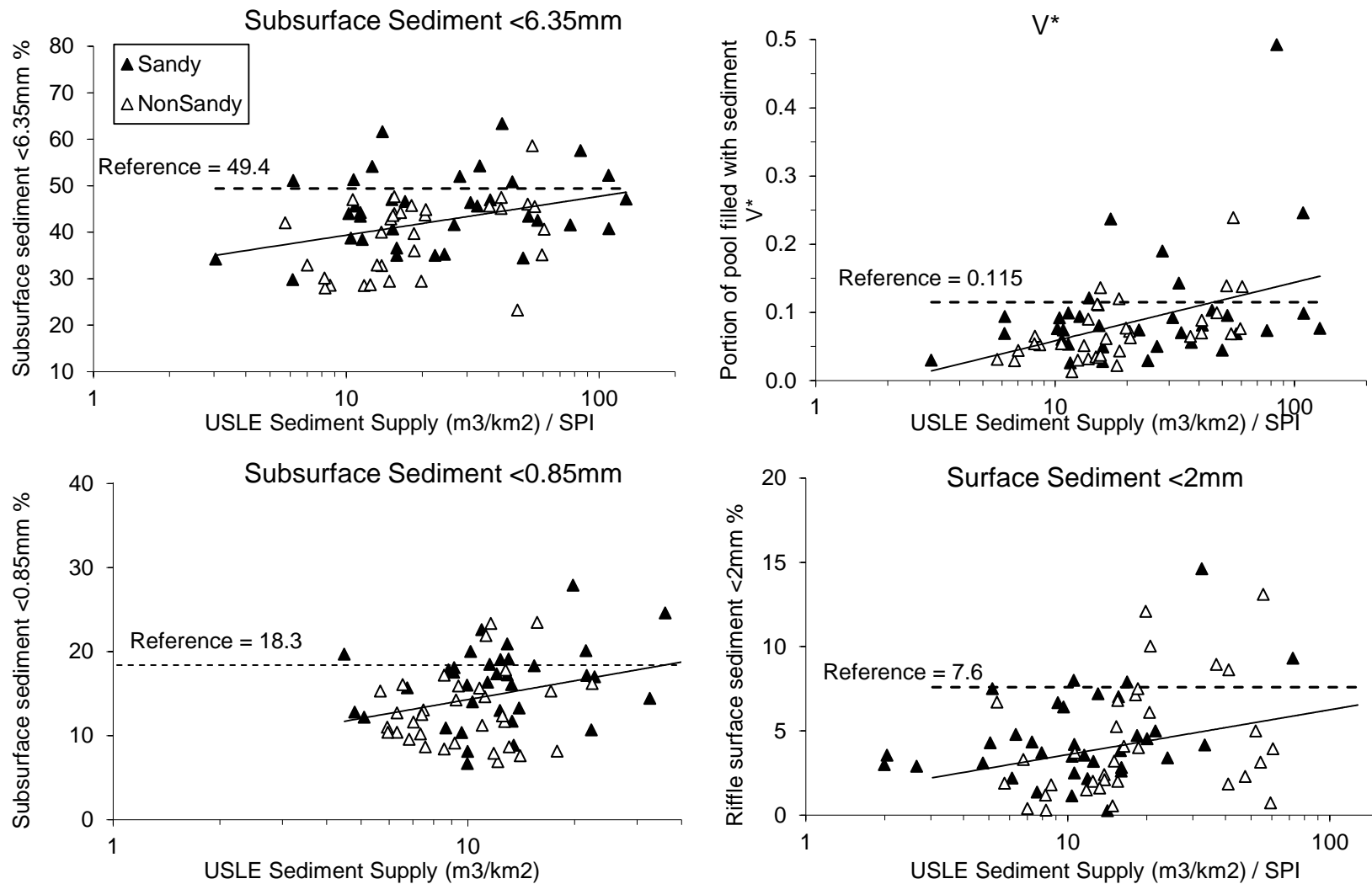


Figure 7. Stream response to USLE sediment supply. Sandy streams have >40% of their drainage area in sandy geology.

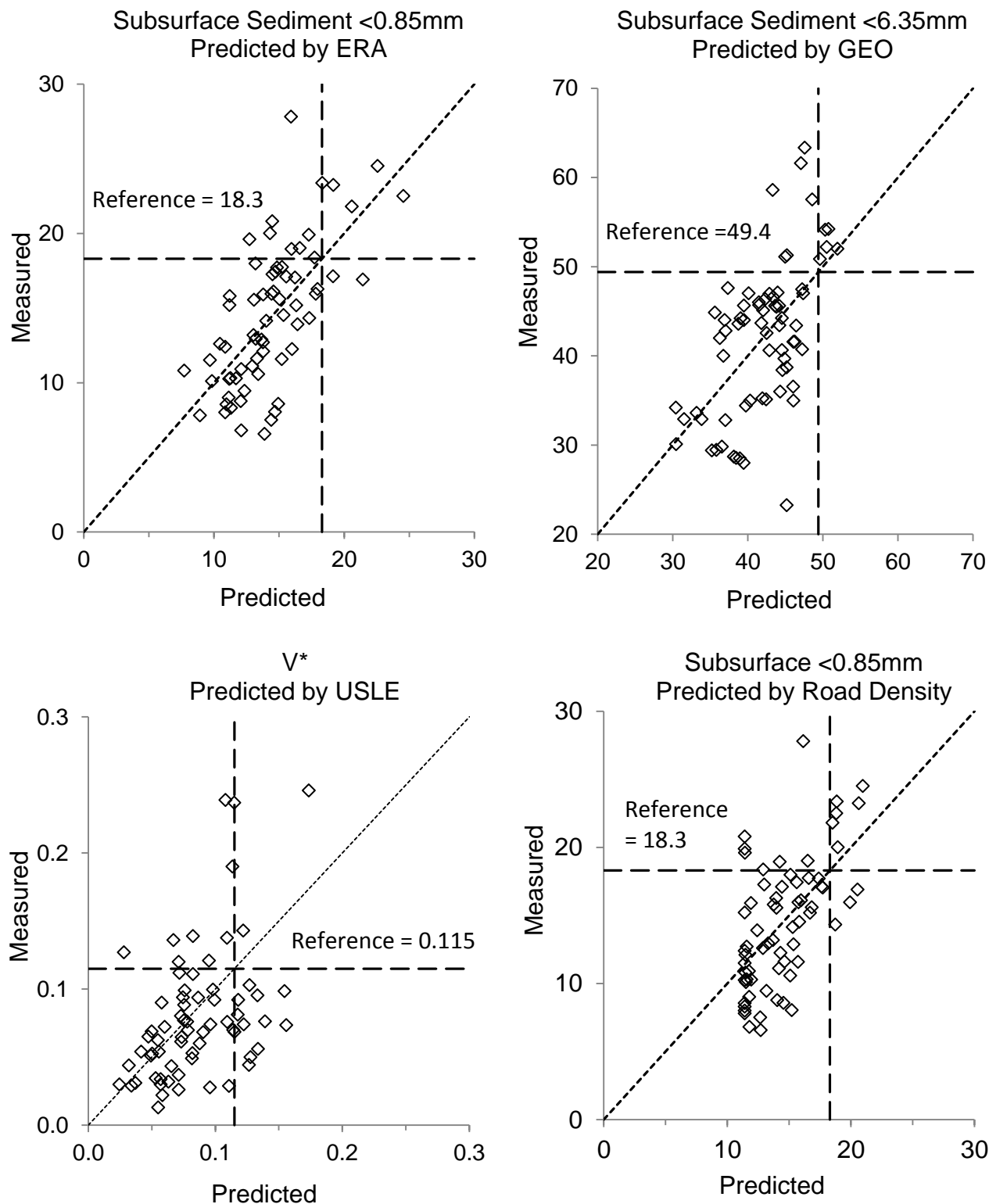


Figure 9. Predicted versus measured sediment for the best models in Table 12 for ERA, GEO, USLE, and Road Density.

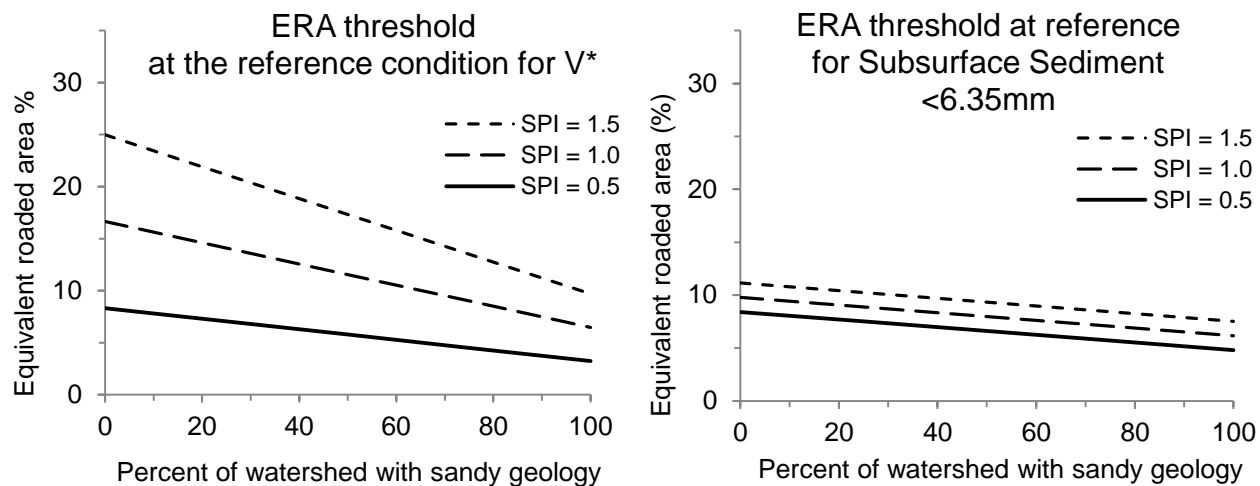


Figure 8. Equivalent roaded area thresholds for attaining reference conditions. The curves were calculated using equations 3 and 2 from Table 11 with V^* and subsurface sediment <6.35mm held constant at 0.115 and 49.4 (the reference values).

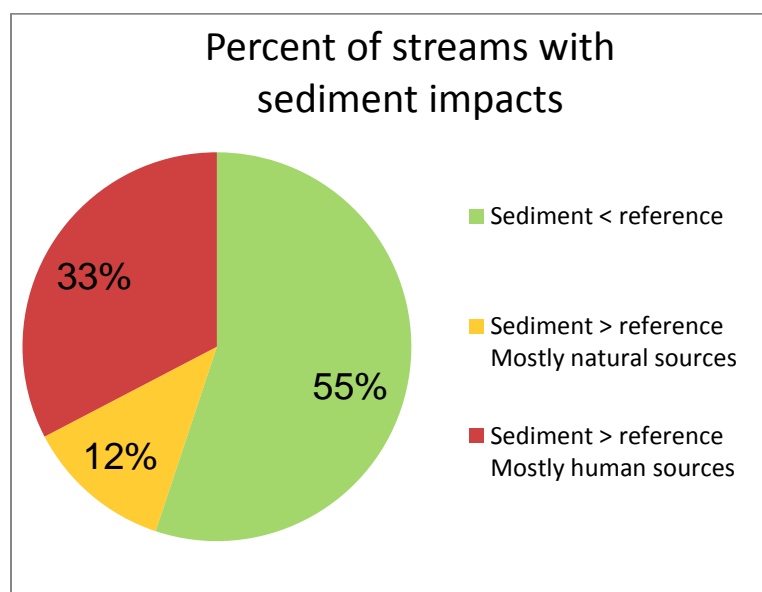


Figure 10. Percentage of streams with in-stream sediment greater or less than the reference condition. .

ACKNOWLEDGEMENTS

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